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THE CONCEPTUAL DESIGN OF A NUCLEAR ELECTRIC POWER SPACECRAFT FOR THE EXPLORATION OF JUPITER

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ABSTRACT

This paper describes the conceptual design of a Jupiter capture spacecraft which utilizes the electrical power output of 1.3 Mw from a nuclear power source to drive an ion engine. Starting with a gross spacecraft weight of 45,000 lb in a 300 n. mi. earth orbit, the tradeoff between terminal mass at Jupiter and flight time to Jupiter utilizing the electric propulsion system is shown. A typical flight trajectory to the target planet is illustrated.

The considerations of the various subsystem requirements and constraints are reviewed briefly and the resulting configuration is shown. A summary of typical system weights and power requirements is listed, and a sequence of operations is described beginning with reactor startup in the earth orbit, following through to the power switch over from the thrust unit, to the scientific experiments upon arrival at the target planet.

Possible scientific experiments at Jupiter are listed and related to the unique characteristics of a nuclear electrical spacecraft. As an example, the high power level available at the completion of the thrust period is utilized to operate a high-powered wide bandwidth transmitter which will allow for transmission of high quality video pictures back to Earth.

I. INTRODUCTION

Programs presently under way in this country will probe the near-Earth planets, Mars and Venus, within the next few years. These missions will use chemically propelled spacecraft. The space scientist, however, is already reaching toward the exploration of the more distant major planets. The desire to accomplish these high energy missions will not be met adequately with chemical rocket designs. Studies have shown, however, that nuclear-electric systems can provide superior capability in meeting these deep space scientific missions.

In order to more fully explore the capabilities of such systems and begin to understand the development problems which must be overcome in the realization of these capabilities, a conceptual design of a typical nuclear-electric powered spacecraft for the unmanned scientific exploration of the planet Jupiter has been undertaken. This conceptual design study, which is reviewed here, was performed by various members of the Advanced Propulsion Engineering Section of the Jet Propulsion Laboratory.

II. PERFORMANCE CONSIDERATIONS

Considering a 45,000-lb spacecraft boosted into a 300 n. mi. Earth orbit by a hypothetical boost vehicle, calculations show that 1 Mwe of electric power driving a 90% efficient ion motor which operates at a specific impulse of 8000 sec will propel the spacecraft from the Earth orbit to the vicinity of Jupiter with the performance shown in Fig. 1. This predicted performance is based on an optimal constant thrust plus coast period trajectory which was adapted from trajectory studies reported in Ref. 1.

If one assumes a nominal 2 to 2 1/2 year lifetime for the energy source and selects a 675-day flight time to Jupiter, then approximately 30, 000 lb of total spacecraft weight can be delivered to the area of the target planet. The nuclear electric energy source will then continue to provide electrical power for scientific experiments and high-powered wide bandwidth radio transmission back to Earth for an additional 2 months or more. From Fig. 1 it can be seen that an even greater total spacecraft weight can be delivered to Jupiter, if one is willing to accept a longer flight time. Longer flight times were not considered appropriate for this study, however, since it is already felt that the selected 2 to 2 1/2 year system lifetime will offer a severe challenge in achieving the necessary hardware reliability.

A typical trajectory for the electric propulsion portion of the flight based on the selected operating parameters will be initiated with a nominal 70 days of powered flight in a spiral path of approximately 295 turns starting in the Earth orbit and gradually increasing until escape as shown in Fig. 2. During this portion of the flight the thrust vector is directed tangentially to the flight path as shown in the figure. This will be followed by a heliocentric transfer of about 145 days of powered flight, 400 days of coasting, and another 60 days of powered flight, ending up in the vicinity of the planet Jupiter as illustrated in Fig. 3. The heliocentric portion of the flight is characterized by a constantly changing thrust vector orientation, as shown in the figure. If guidance constraints are properly met, then the spacecraft will be caught in a highly elliptical orbit about Jupiter. Some 15, 000 lb of propellant, for example, cesium, will be consumed during the powered flight period.

III. CONFIGURATION SELECTION

In arriving at a possible configuration to accomplish this mission, one must first determine the major systems and components which together will form the complete spacecraft. These may be summarized as follows:

1. Power production equipment consisting of a reactor, two turbogeneration units, primary heat rejection radiators, a primary nuclear radiation shadow shield, liquid metal heat transfer loops, and associated controls. (Although this study was conservatively based on a turbogeneration power conversion system, the prospect of direct conversion thermionic systems also appears promising.)
2. Power conditioning equipment to transform, rectify, regulate, and distribute the power to the actual points of utilization.
3. An ion motor consisting of a cluster of modular thrust units.
4. A propellant tank and feed system.
5. Guidance and control equipment.
6. Functional instrumentation and telecommunication equipment including a steerable antenna.
7. Structure and thermal control equipment.
8. The scientific payload.
9. Secondary shielding to protect some highly sensitive components.

Estimating conservative equipment and structure weights, Fig. 4, one finds that approximately 5000 lb of useful scientific equipment, 2000 lb of spacecraft functional instrumentation and high-powered transmitter equipment and a power source providing over 1 Mwe of useful electrical power can be delivered to the capture orbit. Through proper development effort to reduce the weight of such items as the guidance and control equipment, structure, etc., it is expected that the useful payload weight could be increased further.

The nuclear energy source for this spacecraft would provide approximately 8.7 Mwt of thermal power, (reference Fig. 5), to a 15% efficient conversion system which, in turn, would produce 1.3 Mwe of raw electrical power. This power is conditioned by transformation, rectification, and regulation to provide the proper voltage levels for spacecraft use. On the assumption of 90% efficiency, 1.17 Mwe of regulated power is delivered. Of this, 1 Mwe is directed to the ion engine for primary thrust while the remaining 170 kwe provides utility power for guidance, control, powered flight radio transmission, instrumentation, etc. Part of this latter power requirement for control may be used to produce secondary thrust in various directions to affect attitude stabilization.

Considering the significant physical and operational characteristics of the various systems and components which affect spacecraft integration, one may arrive at several generalizations which in turn point the way toward a logical spacecraft configuration.

As a general rule, it appears desirable to locate the elevated temperature devices together at one end of the spacecraft. These devices are usually the sources of nuclear radiation as well. The temperature-sensitive devices, which are frequently radiation sensitive, may then be located at the maximum practical distance at the other end of the spacecraft. Components which require shielding should be located in as small a shadow cone angle as possible to reduce primary shield weight.

Nonsensitive components should also fall within the shield shadow or should at least present the smallest possible cross sectional area for radiation scattering. Preliminary estimates indicate that scatter radiation is a major consideration in determining total shield weights. High-current carrying power lines must be kept short through proper positioning of the ion motor relative to the power conditioning and generation equipment. The propellant load, which represents a changing quantity of mass, should be positioned relative to the ion engine to provide a minimum change to the over-all spacecraft center of mass in order to minimize any control stability problems. Finally, the large heat rejection radiator surfaces must be positioned to provide maximum radiation efficiency, minimum probability for micrometeorite damage, and maximum ease of boost phase packaging. This latter point turns out to be one of the most difficult requirements to meet even at lower power levels.

Figure 6 illustrates a possible configuration for the Jupiter spacecraft which results from the performance, hardware, and operational considerations previously described. The nuclear reactor, primary shield and two turbogeneration units are shown nestled together within the large primary heat rejection radiator at the forward end of the spacecraft. The radiator provides approximately 3500 sq ft of radiating surface at a temperature of 1050°F.

At the aft end of the spacecraft can be seen the propellant tank and ion engine cluster. Sandwiched between the two and taking advantage of any shielding acquired from the propellant mass, one finds the electronic packages and power conditioning equipment. Surrounding this equipment lies the large secondary heat rejection radiator which is required to cool the electronic and power conditioning components. This radiator provides about 1700 sq ft of surface radiating at 200°F. Hopefully, development effort will result in electronic components in the future having higher temperature tolerance which in turn will allow for higher secondary radiator operating temperatures and reduced radiator area.

The ion engine cluster is split in half to minimize interception of the ion beam with the adjacent radiator structure. Steering of the spacecraft might be accomplished by thrust modulation of the ion engine modules.

During the flight from the Earth to Jupiter the spacecraft is oriented such that the radiator discs lie essentially in the plane of the ecliptic. The steerable communication antenna, shown above the propellant tank, is continually directed toward the Earth while the main body of the spacecraft gradually changes direction to satisfy the trajectory requirements previously described.

IV. OPERATIONAL SEQUENCE

A typical sequence of operations to accomplish the desired mission consists of first boosting the dormant spacecraft into a safe, long-lived Earth orbit; for example, a nominal 300 n. mi. orbit. The spacecraft then proceeds to come to active life by unfolding itself as shown in Fig. 7 through 13.

Following this operation the reactor and power generation equipment are started and the thrusting period begins. Thrust continues through the escape spiral and the first portion of the heliocentric transfer until the beginning of the coast period. During this thrusting period various space measurements and functional data from the spacecraft systems can be transmitted back to Earth by a moderately powered transmitter.

For the coasting period several modes of operation may be considered. First, the power generation system may be throttled back to the 10 or 20% level to provide only enough power to keep the spacecraft systems minus the primary ion engine functioning; second, if throttling capability appears to be too ambitious, the unused ion engine power can be dumped into a resistive load and radiated into space as waste heat; or third, the power can be utilized to operate the high-powered transmitter and some major mid-flight space experiments. A possible series of experiments of some interest which might be performed would be ones related to the investigation of the Asteroid belt through which the spacecraft must pass on its way to Jupiter.

Thrusting power would then be resumed to complete the heliocentric transfer. Upon arrival in the vicinity of Jupiter the thrusting would cease and the power would be switched over to the primary planetary experiments and the high-powered transmitter. The spacecraft would remain in this mode until the power source expired or was commanded off.

V. SCIENTIFIC MISSION

The scientific experiments which might be performed at Jupiter would be chosen to take advantage of the unique character of nuclear electric propulsion systems, i.e., the large amount of power which can be made available and the wide bandwidth communication transmitter which can be operated on this power. A typical transmitter radiated power of 50 kwe or more might be used for such a mission. Transmission at this level with appropriate receiver equipment on Earth would allow for the reception of high quality video pictures from Jupiter. Figure 14 summarizes some of the typical scientific experiments which might be performed with an early generation nuclear electric power Jupiter spacecraft (Ref. 2).

The incentive to develop the spacecraft to achieve these scientific goals is shown in Fig. 15, the first of the major planets, Jupiter!

ACKNOWLEDGEMENT

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Particular credit is due Mrs. Evelyn Speiser, William A. Boepple, and Alan S. Wood for the part they played in providing the performance parameters, the detailed spacecraft, and the configuration picture, respectively.

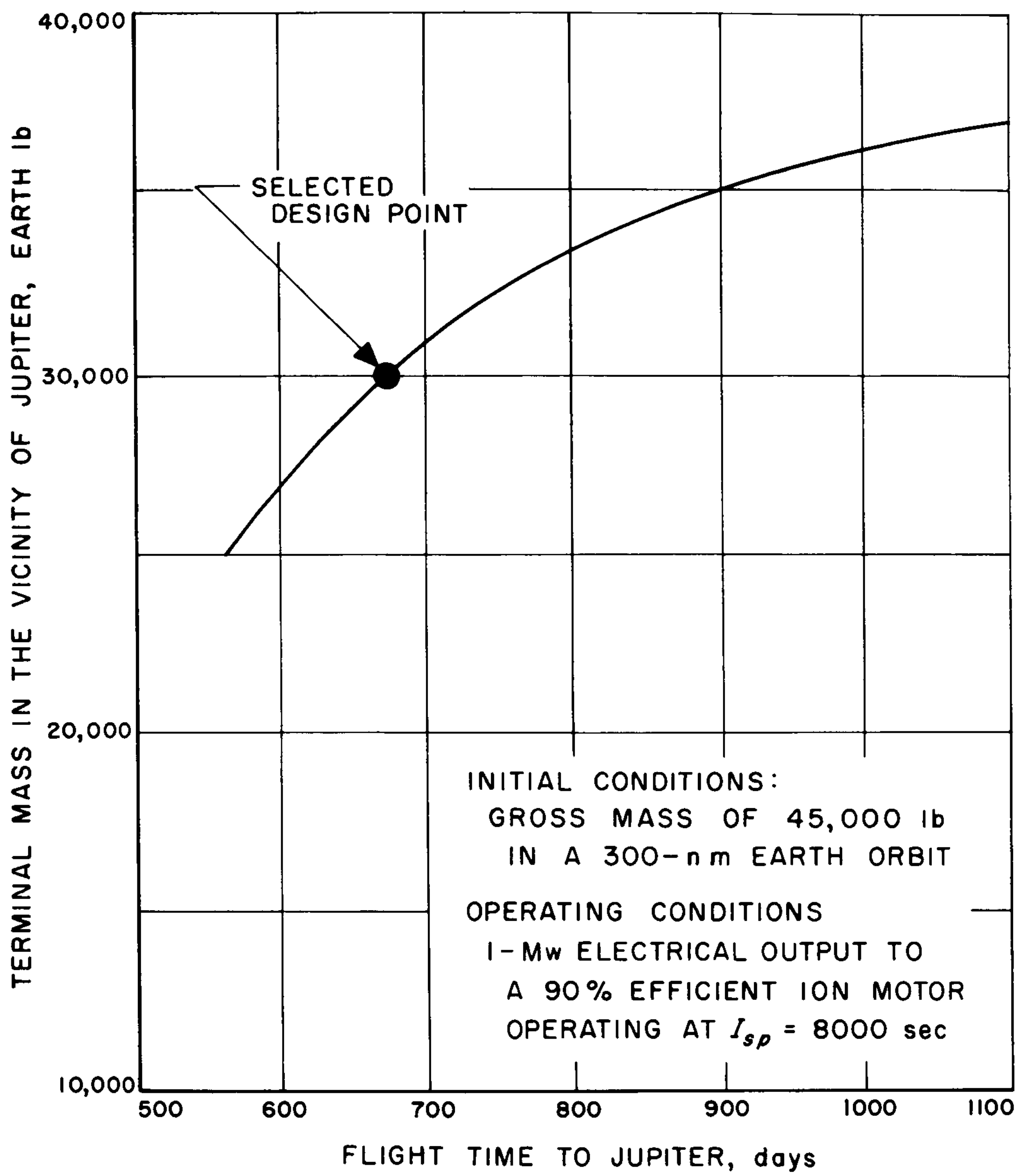

Fig. 1. Jupiter Capture—1-Mw Propulsion Performance Estimate

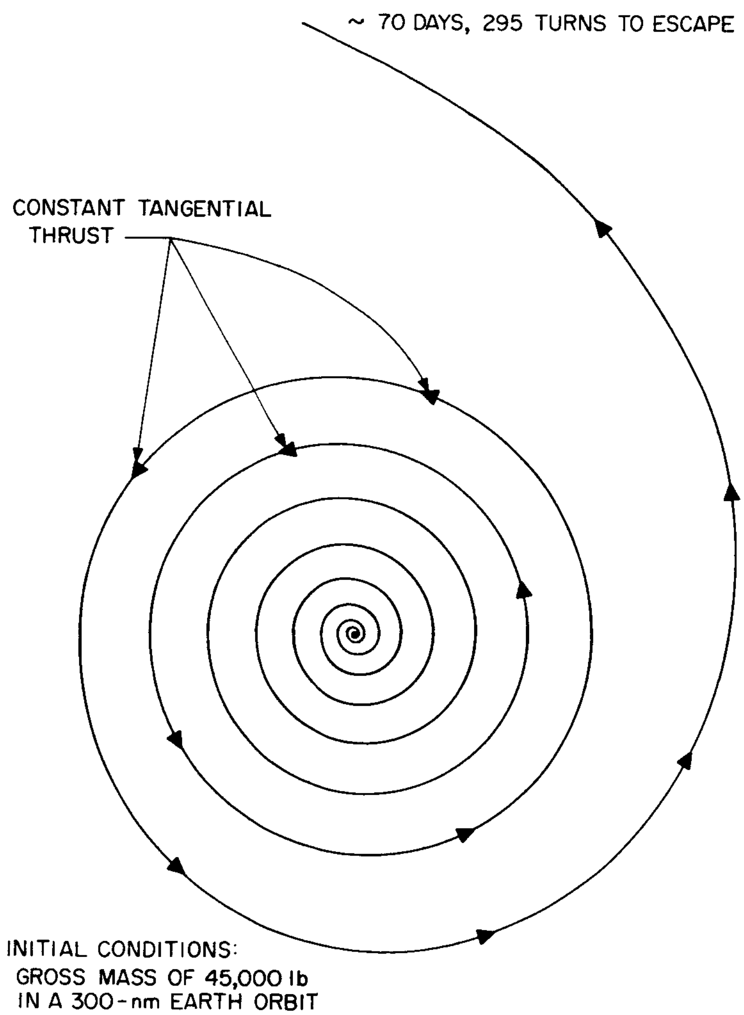

Fig. 2. 1-Mw Propulsion Earth Escape Spiral

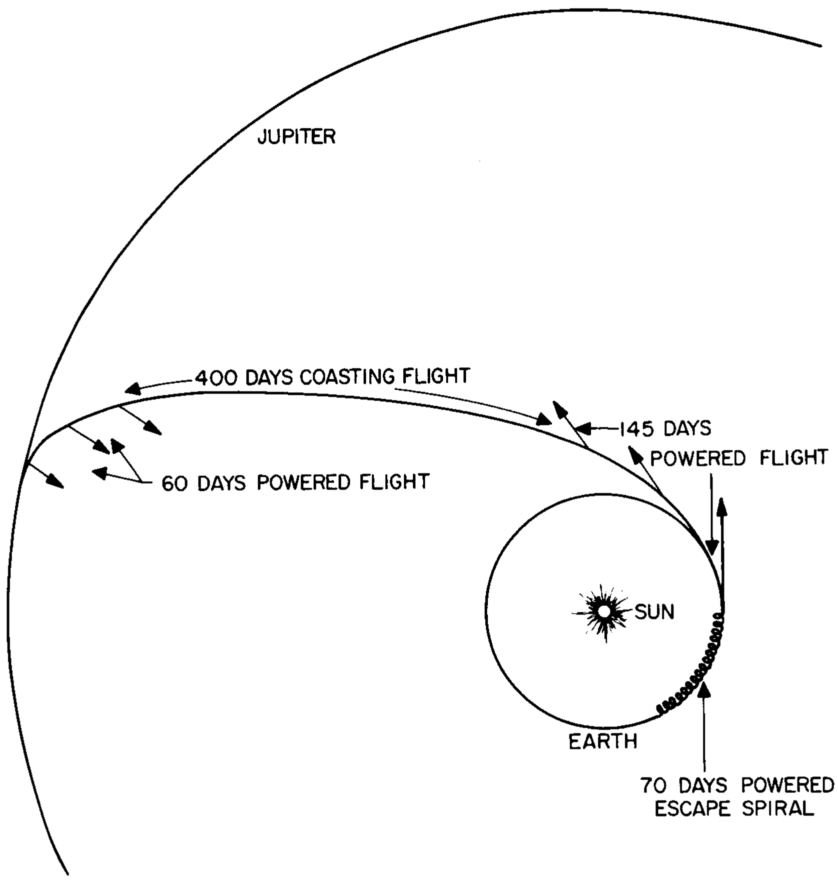

Fig. 3. Jupiter Capture—1-Mw Propulsion Heliocentric Transfer Trajectory

	Weight, lb
Scientific Payload	5000
Instrumentation-Telecommunication	1200
Wideband Transmitter	800
Antenna Dish	100
Guidance and Control	1000
Ion Engine	200
Propellant	15000
Propellant Tank	500
Power Production Equipment	13000
(1 Mw for Propulsion + 0.3 Mw for Utility and Losses)	(Includes Primary Shield)
Power Conditioning Equipment	5200
Secondary Shield	1000
Structure and Thermal Control System	2000
Initial Mass in Earth Orbit	45000

Fig. 4. Jupiter Capture—1-Mw Propulsion Preliminary Weight Summary

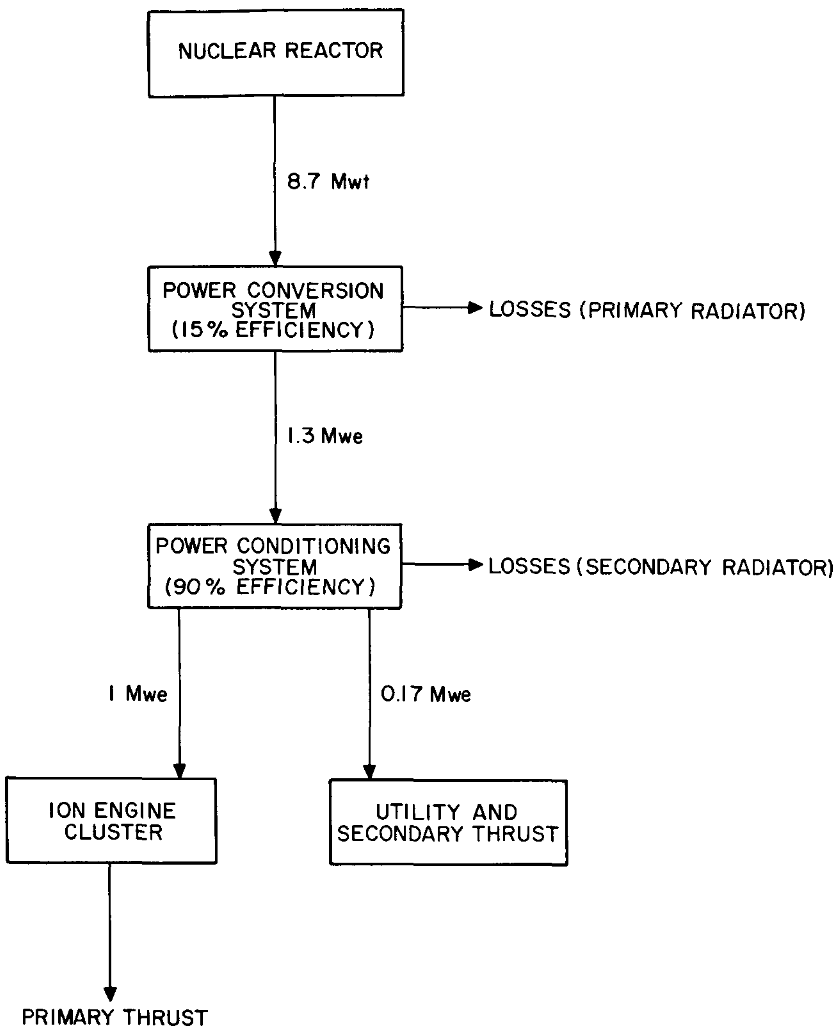

Fig. 5. Jupiter Capture—1-Mw Propulsion Preliminary Power Utilization Summary

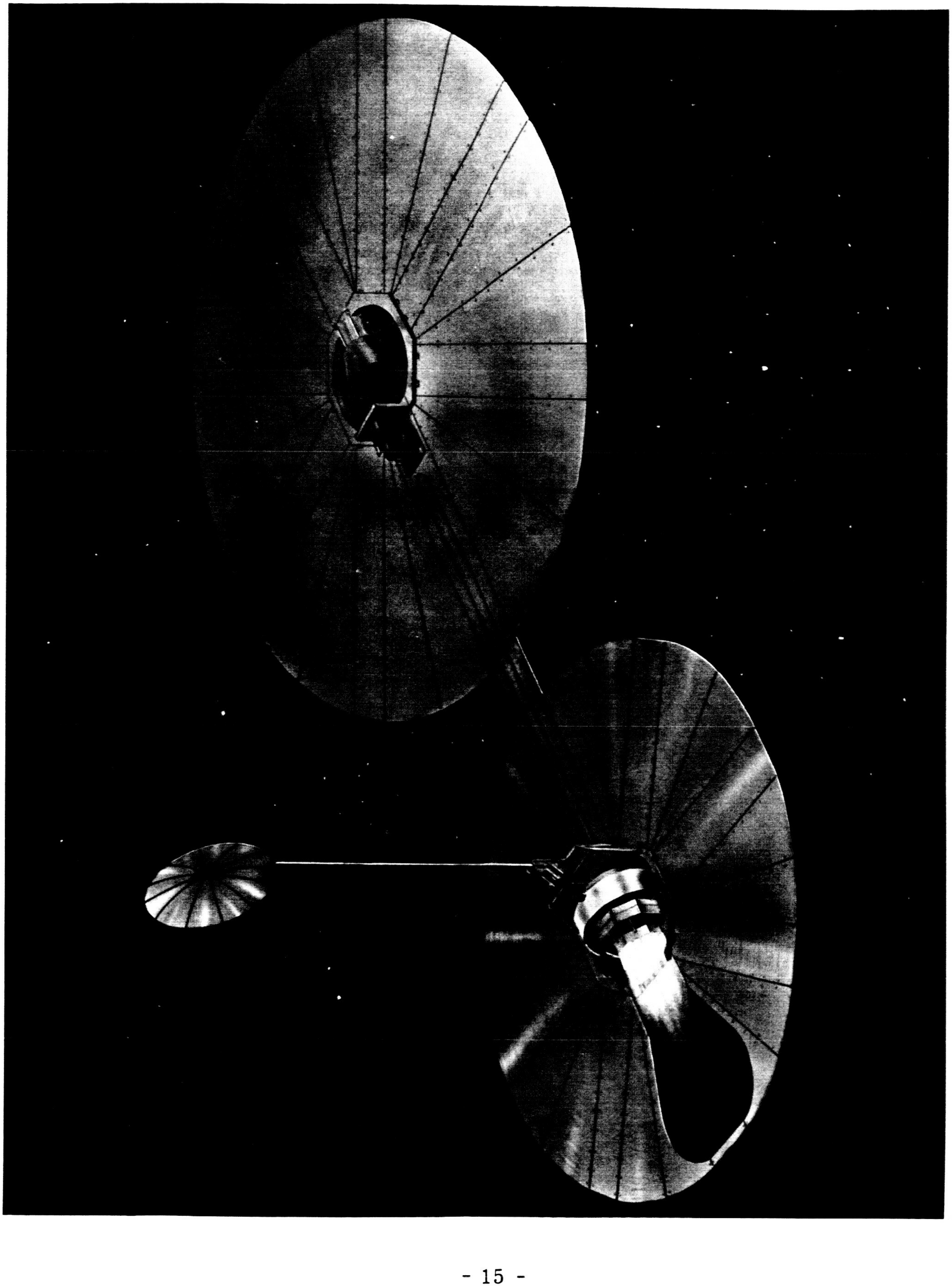

Fig. 6. Jupiter Capture Spacecraft Configuration

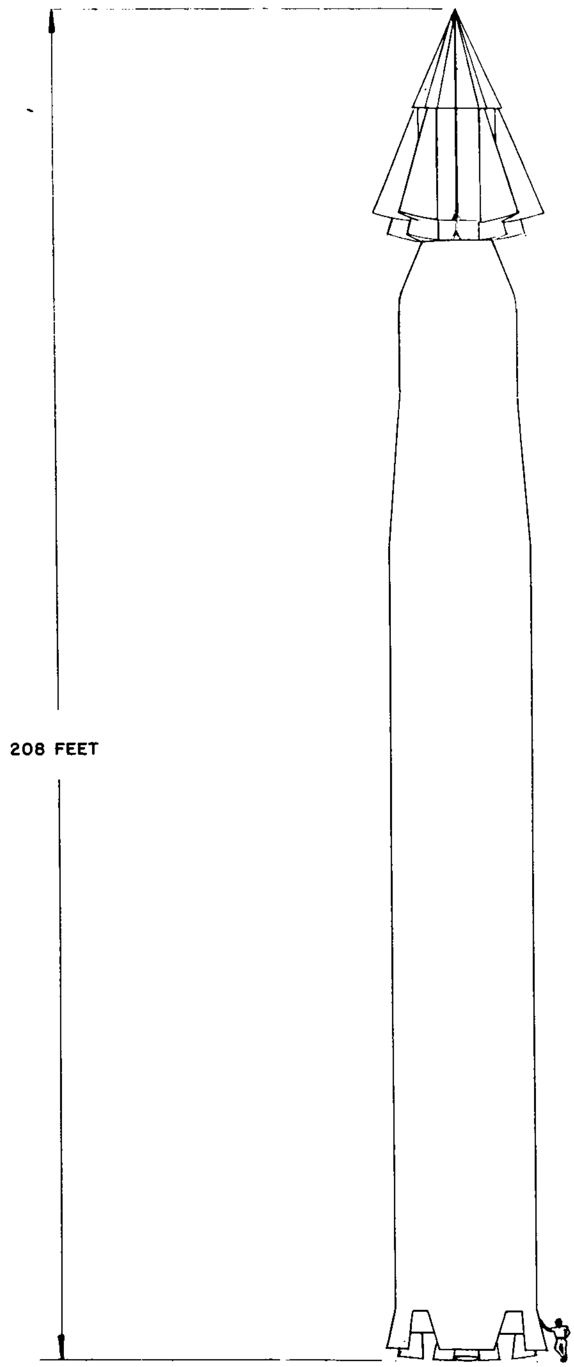

Fig. 7. 1-Mw Jupiter Capture Spacecraft on Booster

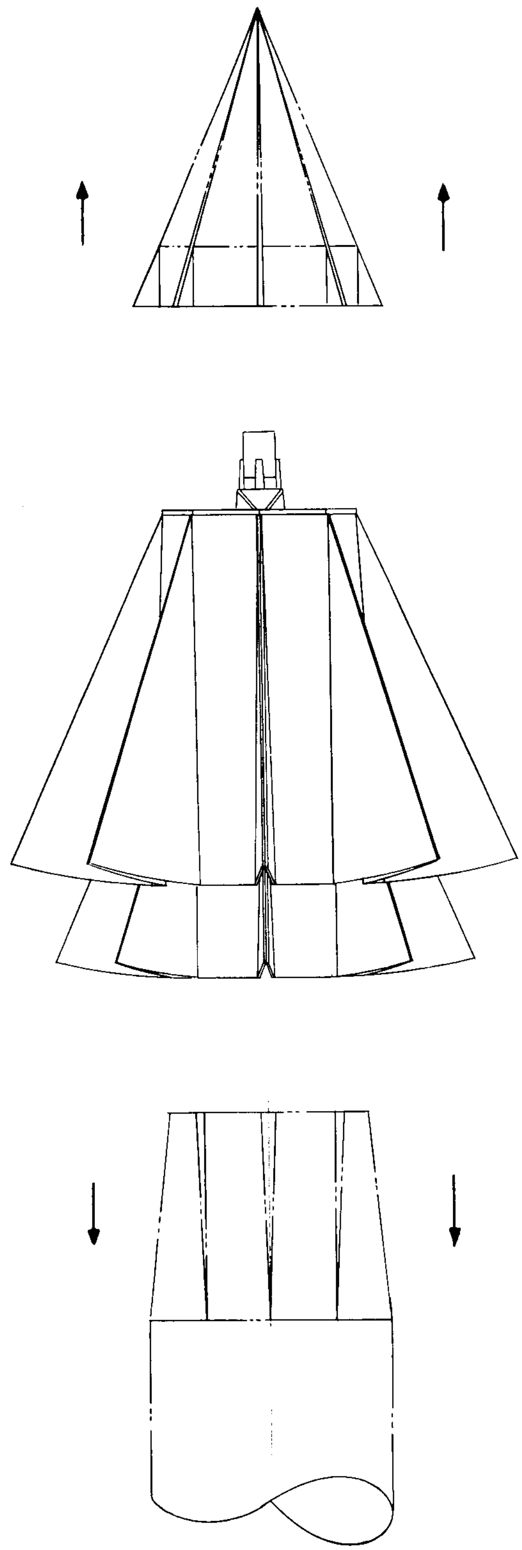

Fig. 8. 1-Mw Jupiter Capture Spacecraft Unfolding Sequence

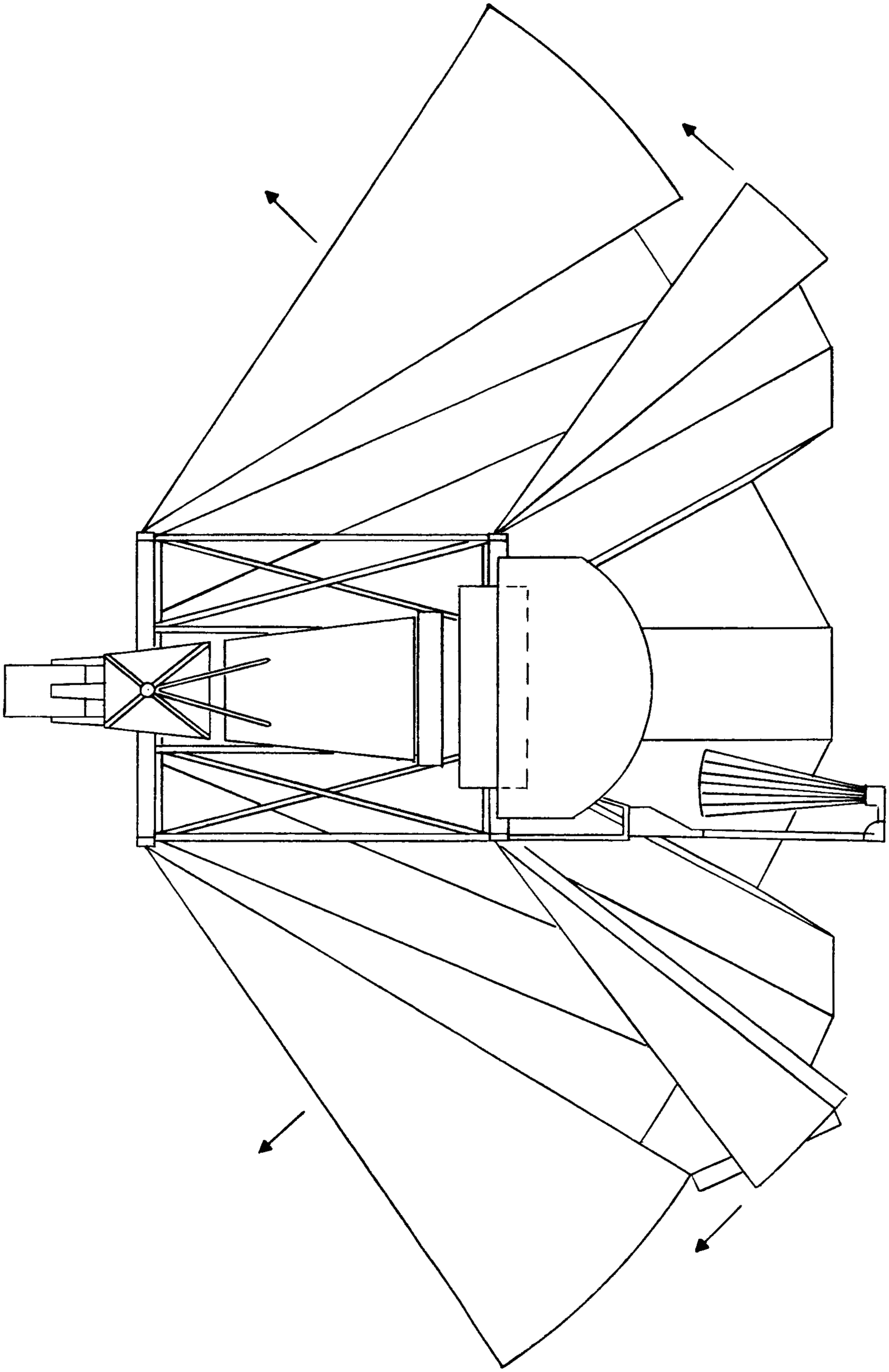

Fig. 9. 1-Mw Jupiter Capture Spacecraft Unfolding Sequence

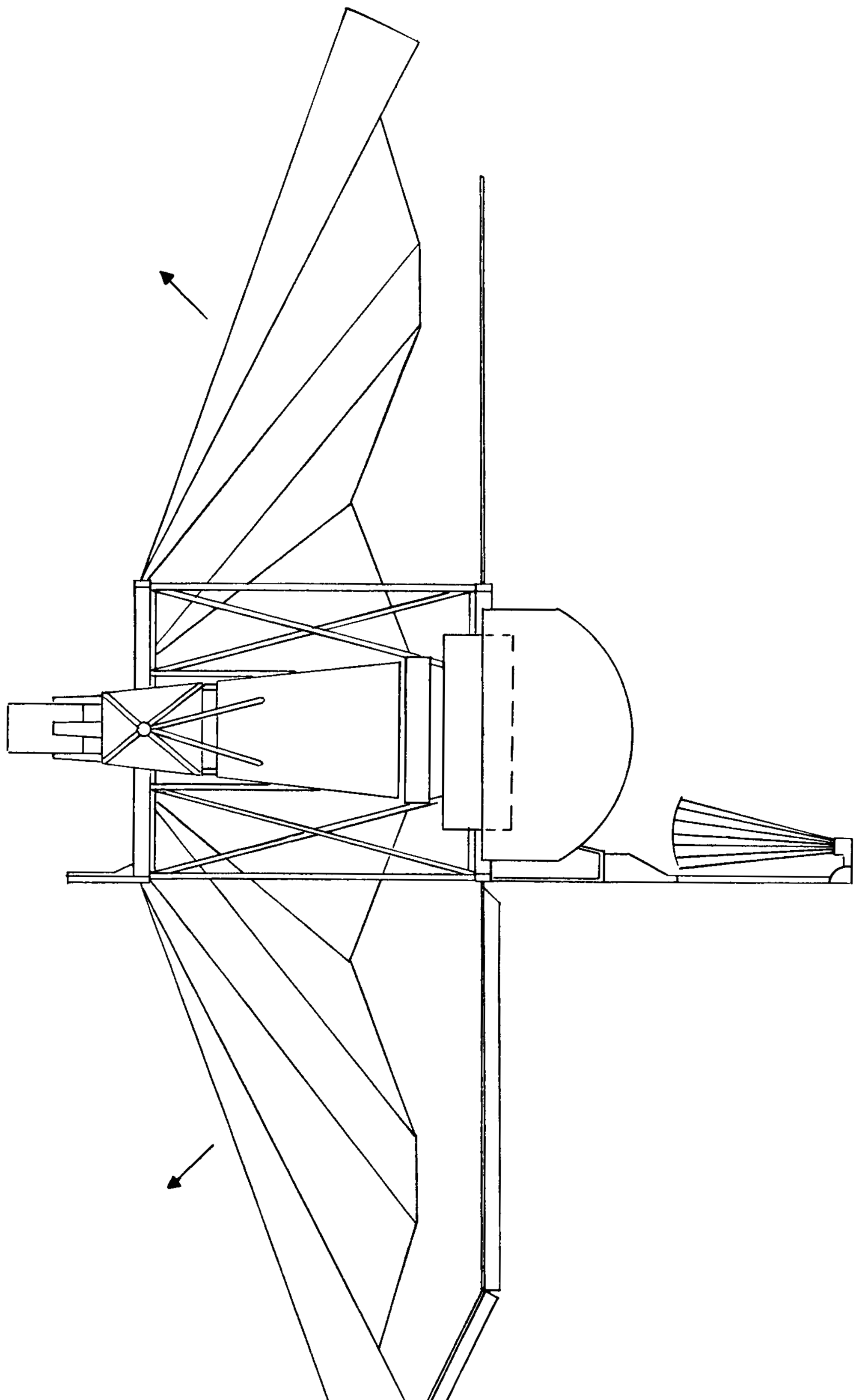

Fig. 10. 1-Mw Jupiter Capture Spacecraft Unfolding Sequence

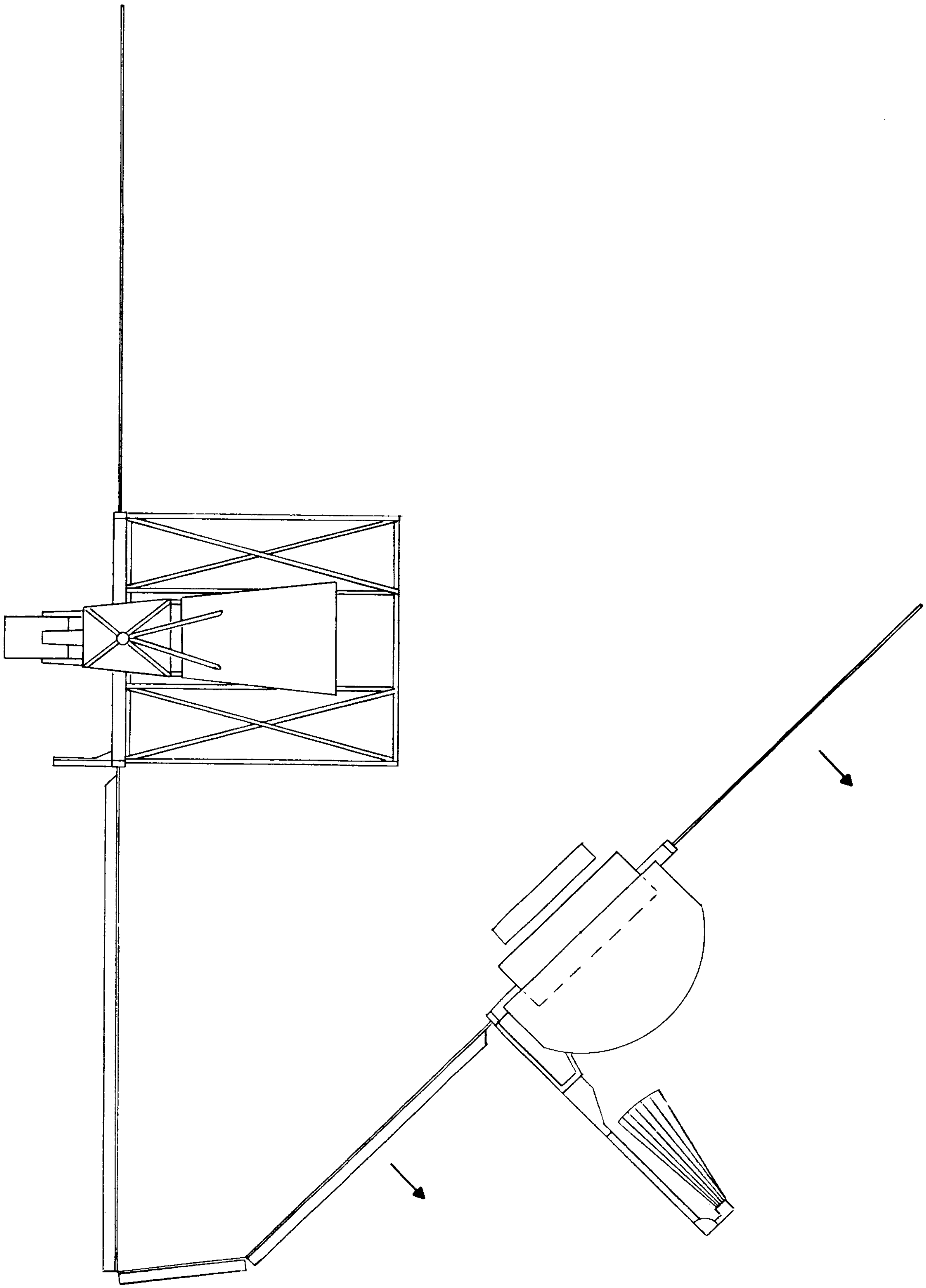

Fig. 11. 1-Mw Jupiter Capture Spacecraft Unfolding Sequence

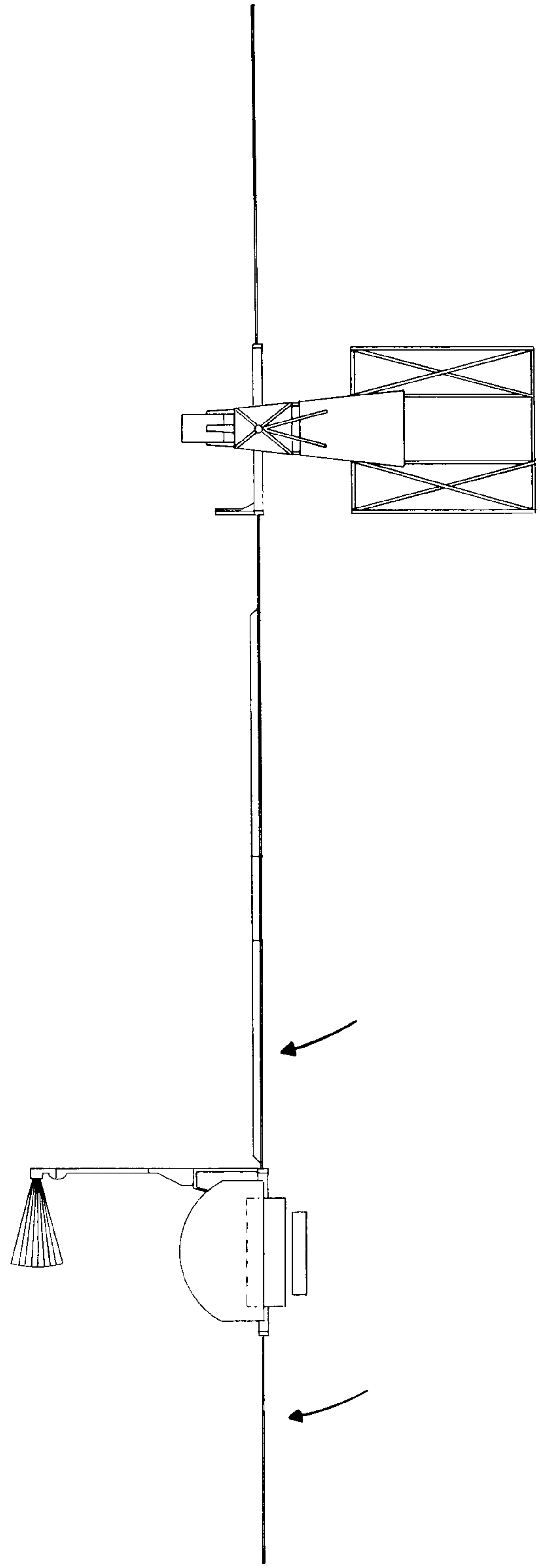

Fig. 12. 1-Mw Jupiter Capture Spacecraft Unfolding Sequence

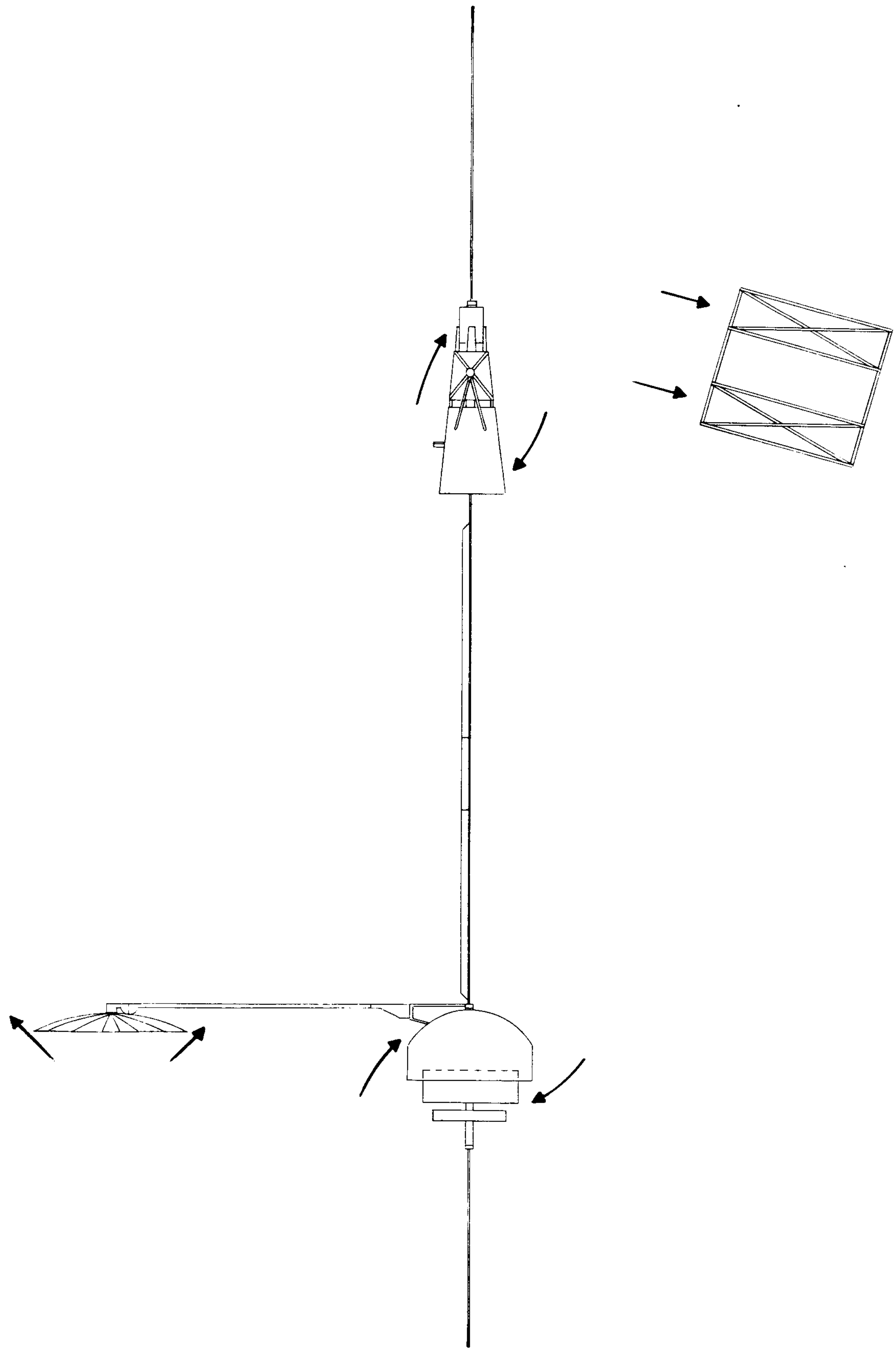

Fig. 13. 1-Mw Jupiter Capture Spacecraft Unfolding Sequence

Magnetic Field Measurements in Interplanetary Space and Adjacent to Jupiter
Spectrophotometric Measurements of the Jovian Atmosphere
Microwave Radiometry Measurements of the Jovian Radiation Belts and Ionosphere
Radar Probing of the Jovian Atmosphere and Planetary Surface
High Resolution Video Pictures of the Jovian Cloud Structure

Fig. 14. Jupiter Capture Spacecraft—Typical Scientific Experiments

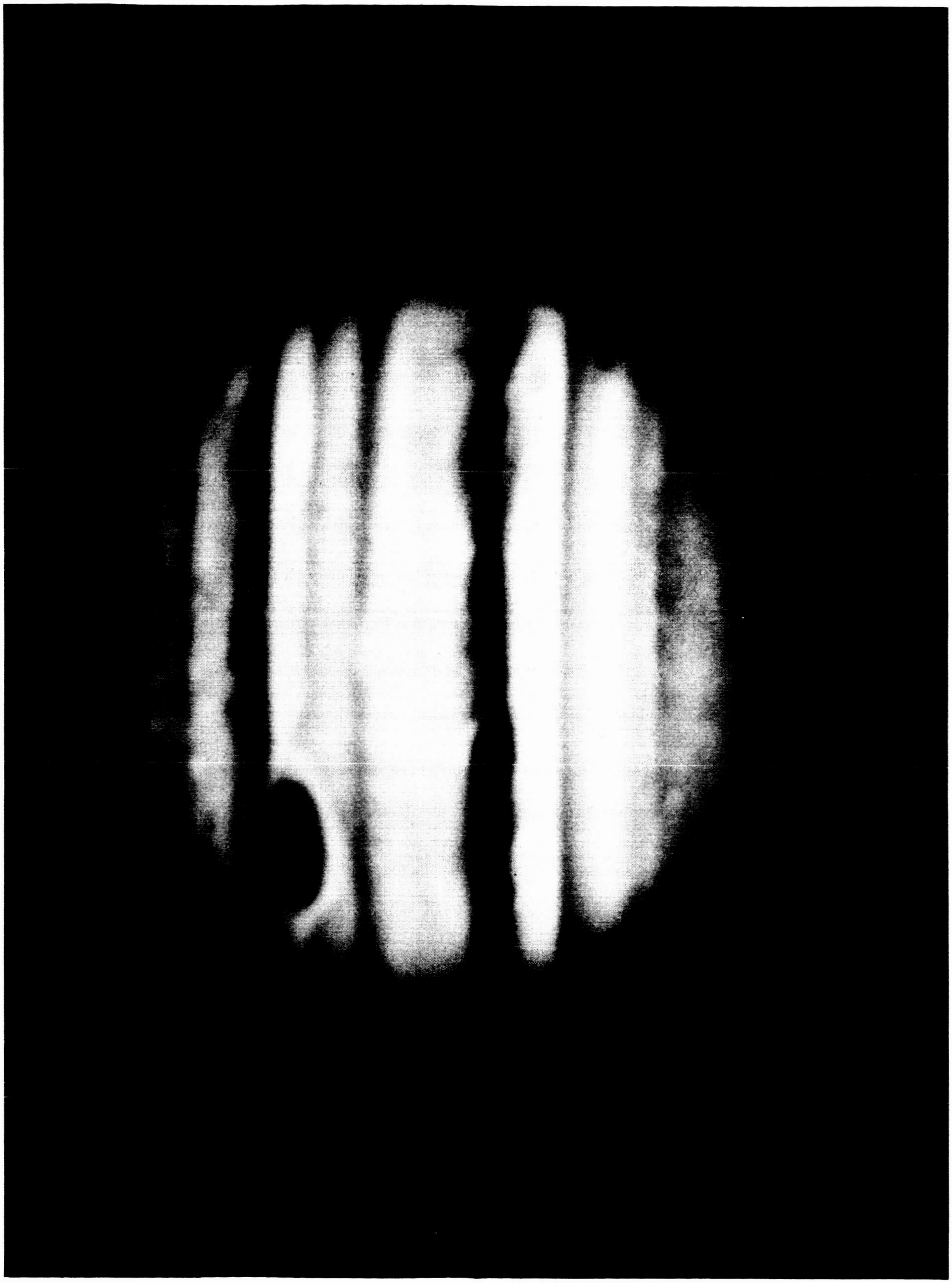

Fig. 15. Jupiter, in Blue Light, Showing Large Red Spot
(Photograph from the Mount Wilson and Palomar Observatories)

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